Titre: Title:	Wide stopband bandpass filter implemented by stepped impedance resonator and multiple in-resonator open stubs
Auteurs: Authors:	Peng Chu, Lei Guo, Long Zhang, & Ke Wu
Date:	2019
Type:	Article de revue / Article
Référence: Citation:	Chu, P., Guo, L., Zhang, L., & Wu, K. (2019). Wide stopband bandpass filter implemented by stepped impedance resonator and multiple in-resonator open stubs. IEEE Access, 7, 140631-140636. https://doi.org/10.1109/access.2019.2943605

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received August 29, 2019, accepted September 20, 2019, date of publication September 25, 2019, date of current version October 8, 2019.
Digital Object Identifier 10.1109/ACCESS.2019.2943605

Wide Stopband Bandpass Filter Implemented by Stepped Impedance Resonator and Multiple In-Resonator Open Stubs

PENG CHU[1,2], (Member, IEEE), LEI GUO[3], LONG ZHANG[4], AND KE WU[2], (Fellow, IEEE)
[1]College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210023, China
[2]Poly-Grames Research Center, Polytechnique Montréal, Montreal, QC H3T 1J4, Canada
[3]School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China
[4]College of Electronics and Information Engineering, Shenzhen University, Shenzhen 518060, China

Corresponding author: Lei Guo (leiguo@dlut.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61601246 and Grant 61601242, and in part by the National and Local Joint Engineering Laboratory of RF Integration and Micro-Assembly Technology under Grant KFJJ20170201.

ABSTRACT Stepped impedance resonator (SIR) has been widely used for applications in wide stopband bandpass filters. However, the reported SIR wide stopband bandpass filters are limited in either stopband performance or design complexity. Here we propose an approach to improve the stopband performance and reduce the design complexity simultaneously. Two in-resonator open stubs are adopted in a SIR (with tap-feeding) to stagger the frequencies of higher-order modes (compared with other SIR) and produce two adjustable transmission zeros without affecting the fundamental properties. For a SIR filter employing such a structure, the spurious passbands are doubly deteriorated by the staggering and up to four transmission zeros. At the same time, the fundamental passband is not affected, which significantly reduces the design complexity. As a result, not only wide stopband but also high-suppression stopband can be obtained in a simple design. A prototype based on the substrate integrated coaxial line (SICL) is experimented showing an impressive stopband performance. Agreeing with the simulation well, the measured stopband is extended up to about 12 f_0 with the suppression of 40 – 50 dB (f_0 is the center frequency). The proposed technique could be very useful to design a bandpass filter with a wide and high-suppression stopband efficiently.

INDEX TERMS Bandpass filter, open stub, substrate integrated coaxial line (SICL), stepped impedance resonator (SIR), wide stopband.

I. INTRODUCTION

The wide and high-suppression stopband is important for a bandpass filter in the microwave/RF circuit and system. However, it is hard to achieve due to the inherent higher-order modes of the microwave resonator, which introduce undesired spurious passbands in the stopband and thus deteriorating the stopband performance. In order to alleviate this problem, many methods have been proposed in the literature such as the capacitive compensation [1], wiggly coupling [2]–[3], corrugated structure [4], over coupled end stages [5], substrate suspension [6], slotted ground [7], capacitive load [8], PBG (photonics bandgap) [9], DGS (defected ground structure) [10], SRR (split ring resonator) [11], SIR (stepped impedance resonator) [12], *etc*. Most of them extend the stopband by suppressing the spurious passband at twice the fundamental frequency ($2f_0$). Differently, the SIR can realize a much wider stopband by pushing the spurious passband to a much higher frequency.

One of the key features of a SIR is that its resonant frequencies can be easily tuned by adjusting the deformation of the linewidth. In a wide stopband bandpass filter, the SIR could at most push the frequency of the first spurious passband to up to $5f_0$ (determined by the fabrication limitation) [13]. Nonetheless, if further wider stopband is required, the spurious passband of a SIR filter still needs to be eliminated. In [13]–[15], the spurious passband of a SIR filter is deteriorated by using dissimilar SIRs to stagger the frequencies of the higher-order modes corresponding to different resonators. In [16]–[17], the spurious passband of a

The associate editor coordinating the review of this manuscript and approving it for publication was Feng Lin.

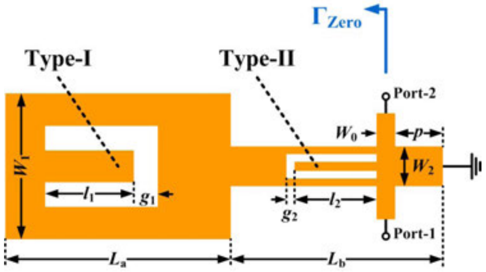


FIGURE 1. Structure of a SIR with two in-resonator open stubs (the width is 1.5 mm and 0.4 mm, respectively). $W_1 = 6$ mm, $W_2 = 2$ mm, $g_1 = 0.5$ mm, $g_2 = 0.15$ mm.

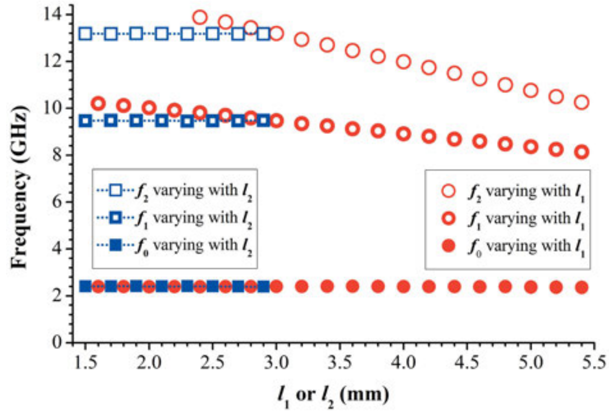


FIGURE 2. Resonant frequencies of a SIR with two in-resonator open stubs. $L_a = 7.65$ mm, $L_b = 7.65$ mm. $l_1 = 3$ mm when l_2 is varying. $l_2 = 2$ mm when l_1 is varying. f_0 is the fundamental frequency. f_1 is the frequency of the first higher-order mode. f_2 is the frequency of the second higher-order mode.

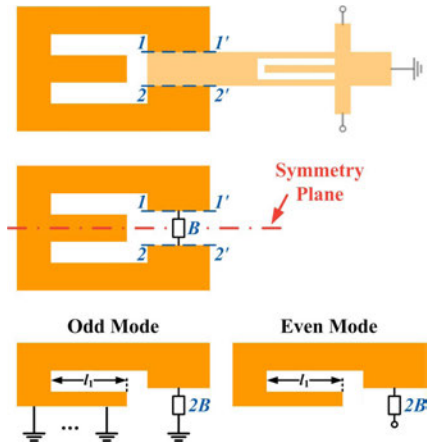


FIGURE 3. Equivalent structure of a SIR with two in-resonator open stubs and that under odd mode operation and even mode operation.

SIR filter is suppressed by utilizing the transmission zeros coming from the tap-feeding. However, it should be noted that the fundamental passband is significantly affected and recovered by introducing other techniques which complicate the design significantly.

It is clear that a spurious passband elimination technique without affecting the fundamental passband of a SIR filter would be of great interest. In [18], staggering the higher-order modes is realized by using in-resonator open stubs with the fundamental frequency unaffected, which realizes the spurious passband deterioration in a very simplified design. However, the stopband can be only extended to 8.76 f_0. By cascading lowpass and bandstop filter, the spurious passband could be also suppressed without affecting the passband response in a sense [19]. However, it will inevitably increase the circuit area and deteriorate the insertion loss. To save the circuit area, the bandstop filter could be simplified to a single open stub [20], which can be embedded in the transmission-line or resonator for more compactness [21]–[24].

Besides the stopband extension, stopband suppression is also very important. However, it is hard to achieve high-suppression if the spurious passband is only suppressed by a single technique as in most of the reported designs.

This paper presents a novel SIR wide stopband filter. The spurious passband is doubly deteriorated by staggering the high-order modes and introducing multiple transmission zeros, which is implemented by using multiple in-resonator open stubs without affecting the fundamental passband. As a result, in a simple design, not only wide stopband but also high-suppression stopband can be obtained.

II. PROPERTIES

This section investigates the properties of a SIR with two in-resonator open stubs in order to facilitate the wide stopband bandpass filter design in the next section.

Fig. 1 shows a SIR with two in-resonator open stubs, which are labeled as Type-I near the open end of the SIR and Type-II near the tap point, respectively. For demonstration, the designs in this section are based on microstrip with a substrate of 0.508 mm Rogers RT/duroid 5880 ($\varepsilon_r = 2.2$, tan$\delta = 0.0009$). The simulated data is obtained by using Ansoft HFSS.

A. RESONANT FREQUENCY

Fig. 2 (red icon) shows the resonant frequencies of the SIR varying with the length of the Type-I in-resonator opens stub (l_1). Obviously, the frequency of the fundamental mode is almost unchanged, whereas those of the higher-order modes are manipulated by tuning l_1. This property can be explained by using an equivalent circuit model composed of lumped inductance and capacitance as shown in [18]. However, due to the lumped elements cannot illustrate the higher-order resonant modes, the validity of the equivalence is based on optimization and thus it is hard to truly reveal the principle. Here we present a principle illustration by adopting the even/odd mode analysis.

As shown in Fig. 3, the section from the ground end to 11′ and 22′ can be equivalent to a component with admittance $\boldsymbol{B}$. In this situation, the odd/even mode analysis can be adopted to characterize it since the structure is symmetric [25]–[26]. For the odd mode, a virtual ground can be considered along the symmetry plane, which leads to an approximate equivalent circuit showing in the lower left of Fig. 3. For the analysis of

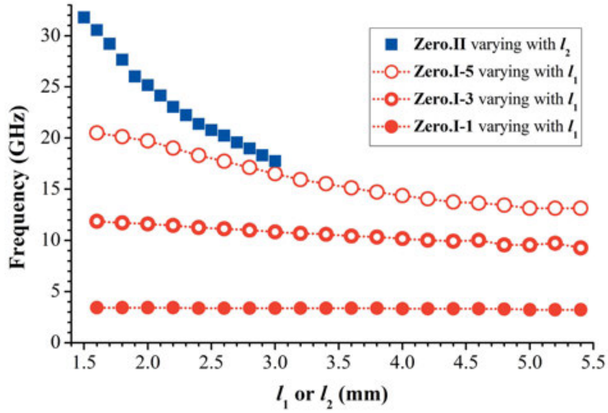


FIGURE 4. Transmission zeros accompanying a SIR with two in-resonator open stubs and tap-feeding. L_a = 7.65 mm, L_b = 7.65 mm. l_1 = 3 mm when l_2 is varying. l_2 = 2 mm when l_1 is varying.

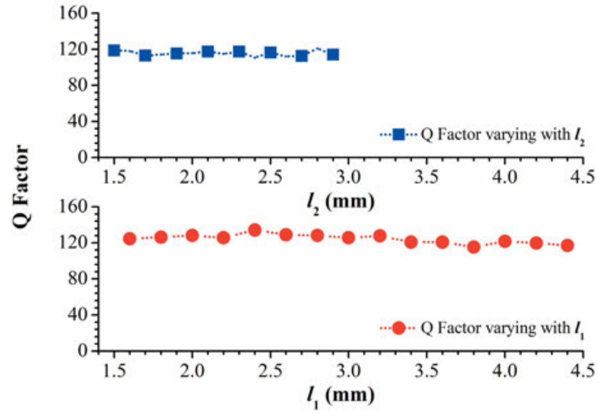


FIGURE 5. Quality factor of a SIR with two in-resonator open stubs. L_a = 7.65 mm, L_b = 7.65 mm. l_1 = 3 mm when l_2 is varying. l_2 = 2 mm when l_1 is varying.

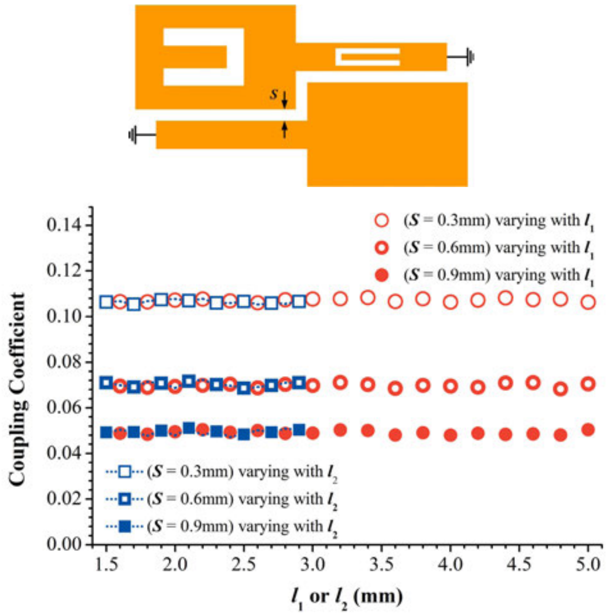


FIGURE 6. Inter-coupling of a classic SIR and a SIR with two in-resonator open stubs. L_a = 7.4 mm, L_b = 7.9 mm. l_1 = 3 mm when l_2 is varying. l_2 = 2 mm when l_1 is varying.

the even mode operation, a virtual open-end is regarded along the symmetry plane, which leads to an approximate equivalent circuit showing in the lower right of Fig. 3. Therefore, it is obvious that the fundamental frequency corresponding to the odd mode is irrelevant to the l_1, while the first higher-order mode corresponding to the even mode is dependent on the l_1.

On the other hand, Fig. 2 (blue icon) also shows the influence of the Type-II in-resonator opens stub (l_2). Different from the effect of l_1, l_2 has little effect on the resonant frequencies of the SIR. That is because no additional current path is provided at the open end as the Type-I one does.

As a result, one can use the structure showing in Fig. 1 to stagger the frequencies of the higher-order modes corresponding to different resonators in a SIR filter, and thus deteriorates the spurious passbands as in [13]–[15]. Moreover, here the fundamental frequency is not affected, which significantly simplifies the design compared with [13]–[15].

B. TRANSMISSION ZEROS

As illustrated in [16] and [27], a resonator with tap-feeding as shown in Fig. 1 can produce transmission zeros. The transmission zeros come from treating the left side of the SIR from the tap point (Γ_{Zero}) as an $n\lambda/4$ (n = 1, 3, 5…) stub so that the input impedance at the tap point is virtually short-circuited. For the structure showing in Fig. 1, the electrical lengths (in other words, the resonant frequencies) can be tuned by l_1 of Type-I stub as illustrated above. Therefore, the frequencies of the transmission zeros can also vary with l_1 as shown in Fig. 4 (red icon), where the Zero.I-n represents the zero corresponding to the aforementioned $n\lambda/4$ (n = 1, 3, 5…) stub. In practical applications, the adjustable Zero.I-3 and Zero.I-5 could be employed to suppress the spurious passband.

The Type-II in-resonator open stub can provide another adjustable transmission zero (Zero.II) to suppress the spurious passband in higher frequency and then further extend the stopband. Here the Type-II stub simply works as a $\lambda/4$ stub to provide a virtual ground at the tap point [21]–[24], and thus the frequency of Zero.II is directly determined by l_2 as shown in Fig. 4 (blue icon). It should be noted that the Type-II stub is not suitable for working at relatively low frequency. That is because, in low frequency, the stub would be too long to be embedded in the SIR, which would significantly affect the properties of the SIR as well.

As a result, one can also use the structure showing in Fig. 1 to produce multiple transmission zeros to suppress the spurious passband of a SIR filter without affecting the fundamental passband. For a two-port filter employing such a structure twice, the number of the transmission zeros can be double.

C. QUALITY FACTOR AND COUPLING

Fig. 5 gives the quality factor of the SIR varying with l_1 (red icon) and l_2 (blue icon). Fig. 6 shows the inter-coupling of a

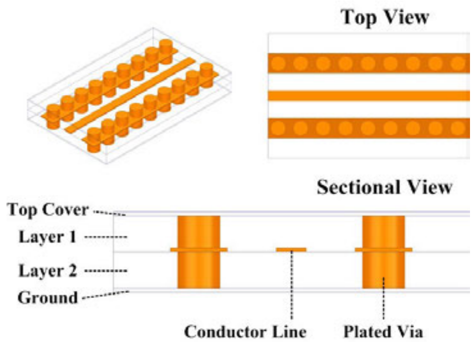


FIGURE 7. Structure of the substrate integrated coaxial line (SICL).

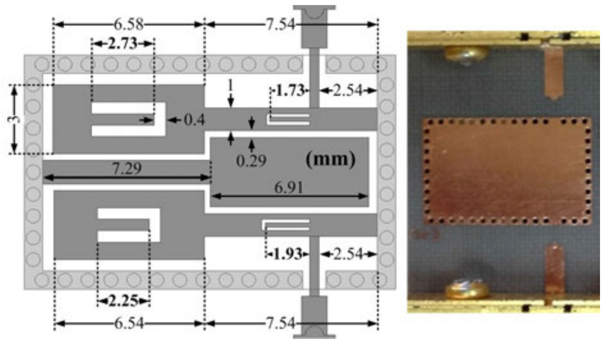


FIGURE 8. Structure and photograph of the prototype filter.

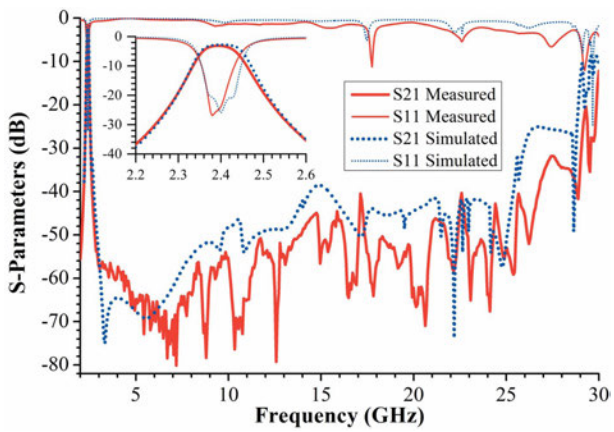


FIGURE 9. Results of the prototype filter.

classic SIR and a SIR with two in-resonator open stubs varying with l_1 (red icon) and l_2 (blue icon). As can be observed, the deterioration of the quality factor and the change of the coupling can be neglected. That is because the skin effect makes the current concentrate at the edge rather than in the area of the stubs.

Therefore, the classic filter design procedure can be still employed to design the fundamental passband of a wide stopband bandpass filter implemented with the structure showing in Fig. 1.

III. FILTER DESIGN

This section provides a guideline to design a wide stopband bandpass filter implemented by the proposed technique.

Step-1: Design a classic SIR filter with tap-feeding.

Step-2: Place two Type-I in-resonator open stubs in the two tap-feeding resonators. The two stubs produce two transmission zeros (Zero.I-3 and Zero.I-5, respectively) to suppress the two leading spurious passbands in the stopband. At the same time, the frequency staggering of the higher-order modes is also achieved, which deteriorates the remaining spurious passbands to be little spurs.

Step-3: Set up two Type-II in-resonator open stubs in the two tap-feeding resonators. Another two transmission zeros (Zero.II) are generated to suppress the remaining spurs, which further extends the stopband.

It should be mentioned that the fundamental passband response is almost not affected during the whole procedure. A wide stopband bandpass filter is obtained after a necessary fine-tuning.

IV. EXPERIMENT

This section provides an experiment to verify the proposed technique. In order to get better performance, the substrate integrated coaxial line (SICL) is introduced here as well [28], which is quite suitable for high-performance wideband applications [29]–[32]. The structure of the SICL is shown in Fig. 7, which is composed of the conductor line, top cover, ground, and plated via array. The conductor line is used to fabricate the proposed filter. The rest of the structure forms a SIW (substrate integrated waveguide) likeness cavity functioning as a shielding box in this paper, so that lesser radiation, lower interference, better insertion loss and electromagnetic compatibility can be obtained. In conventional designs, the shielding box is made of an additional metal box, which can be avoided here since all the components are fabricated in PCB (printed circuit board). Notably, here the SIW likeness cavity doesn't work as a SIW, because SIW is a dispersive transmission structure which is entirely unsuitable for an ultra-wideband application such as the proposed filter [33]. As a nondispersive transmission structure, SICL is very suitable to form the proposed filter and the shielding box without introducing spurious frequency in a wideband. In this paper, the SICL is fabricated by using two-layer Taconic TLY-5 ($\varepsilon_r = 2.2$, tan$\delta = 0.0009$) substrate with a total thickness of 0.508 mm which is bonded by the Taconic TPG-30 ($\varepsilon_r = 3$, tan$\delta = 0.0038$) with a thickness of 0.12 mm.

According to the design guideline illustrated above, first of all, a classic SIR bandpass filter based on the SICL with tap-feeding is designed ($f_0 = 2.4$ GHz, 3-dB bandwidth = 100 MHz) [30], [34]. Then four in-resonator open stubs are employed to deteriorate and suppress the spurious passband. Fig. 8 shows the final structure and dimension. The circuit size (excluding the tap lines) is about $0.129\ \lambda_0 \times 0.081\lambda_0$ (λ_0 is the free space wavelength at f_0).

The prototype is measured by the Agilent N5245A Network Analyzer (10 MHz to 50 GHz) and Anritsu Test Fixture 3680V (DC to 60 GHz). The results are shown in Fig. 9.

TABLE 1. Comparison with State-of-the-Art.

	f_0 (GHz)	FBW (%)	IL (dB)	Order of Filter	Stopband Extension	Stopband Rejection
[13]	2	7.6	2.6	4	11.4 f_0	27.5 dB
[16]	1.5	10	3	5	8.2 f_0	30 dB
[18]	2.4	5	2.4	3	8.76 f_0	40 dB
This work	2.39	3.8	3	3	12 f_0	40 – 50 dB

FBW: 3-dB Fractional Bandwidth IL: Insertion Loss

The measured stopband is extended up to about 12 f_0 with the suppression of 40 – 50 dB. A comparison with the state of the art is given in Table I. It can be observed that the proposed filter shows the best stopband extension and suppression. Notably, the best stopband suppression is realized by using the smallest order (traditional design usually makes use of a higher-order filter to achieve better stopband suppression). It should be noted again that the fundamental passband is almost not affected by the proposed technique, which would significantly simplify the design of a wide stopband bandpass filter.

V. CONCLUSION

A novel method to realize wide and high-suppression stopband bandpass SIR filter in a simple design is presented in this paper by introducing multiple in-resonator open stubs which can not only stagger the frequencies of the higher-order modes but also produce multiple adjustable transmission zeros without affecting the fundamental frequency. An experiment based on SICL showing an impressive stopband performance verifies the proposed technique well. It should become a competitive candidate for the development of RF/microwave circuits and systems.

REFERENCES

[1] I. J. Bahl, "Capacitively compensated high performance parallel coupled microstrip filters," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 1989, pp. 679–682.

[2] T. Lopetegi, M. A. G. Laso, J. Hernandez, M. Bacaicoa, D. Benito, M. J. Garde, M. Sorolla, and M. Guglielmi, "New microstrip 'Wiggly-Line' filters with spurious passband suppression," *IEEE Trans. Microw. Theory Techn.*, vol. 49, no. 9, pp. 1593–1598, Sep. 2001.

[3] T. Lopetegi, M. A. G. Laso, F. Falcone, F. Martin, J. Bonache, J. Garcia, L. Perez-Cuevas, M. Sorolla, and M. Guglielmi, "Microstrip 'Wiggly-Line' bandpass filters with multispurious rejection," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 11, pp. 531–533, Nov. 2004.

[4] J.-T. Kuo, W.-H. Hsu, and W.-T. Huang, "Parallel coupled microstrip filters with suppression of harmonic response," *IEEE Microw. Wireless Compon. Lett.*, vol. 12, no. 10, pp. 383–385, Oct. 2002.

[5] J.-T. Kuo, S.-P. Chen, and M. Jiang, "Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses," *IEEE Microw. Wireless Compon. Lett.*, vol. 13, no. 10, pp. 440–442, Oct. 2003.

[6] J.-T. Kuo, M. Jiang, and H.-J. Chang, "Design of parallel-coupled microstrip filters with suppression of spurious resonances using substrate suspension," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 1, pp. 83–89, Jan. 2004.

[7] M. C. Velazquez-Ahumada, J. Martel, and F. Medina, "Parallel coupled microstrip filters with ground-plane aperture for spurious band suppression and enhanced coupling," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 3, pp. 1082–1086, Mar. 2004.

[8] M. Orellana, J. Selga, P. Vélez, M. Sans, A. Rodríguez, J. Bonache, V. E. Boria, and F. Martín, "Design of capacitively loaded coupled-line bandpass filters with compact size and spurious suppression," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 4, pp. 1235–1248, Apr. 2017.

[9] F. R. Yang, K. P. Ma, Y. Qian, and T. Itoh, "A uniplanar compact photonic-bandgap (UC-PBG) structure and its applications for microwave circuits," *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 8, pp. 1509–1514, Aug. 1999.

[10] J.-S. Park, J.-S. Yun, and D. Ahn, "A design of the novel coupled-line bandpass filter using defected ground structure with wide stop-band performance," *IEEE Trans. Microw. Theory Techn.*, vol. 50, no. 9, pp. 2037–2043, Sep. 2002.

[11] J. Garcia-Garcia, F. Martin, F. Falcone, J. Bonache, I. Gil, T. Lopetegi, M. A. G. Laso, M. Sorolla, and R. Marques, "Spurious passband suppression in microstrip coupled line band pass filters by means of split ring resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 9, pp. 416–418, Sep. 2004.

[12] M. Makimoto and S. Yamashita, "Bandpass filters using parallel coupled stripline stepped impedance resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 28, no. 12, pp. 1413–1417, Dec. 1980.

[13] S.-C. Lin, P.-H. Deng, Y.-S. Lin, C.-H. Wang, and C. H. Chen, "Wide-stopband microstrip bandpass filters using dissimilar quarter-wavelength stepped-impedance resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 3, pp. 1011–1018, Mar. 2006.

[14] C.-F. Chen, T.-Y. Huang, and R.-B. Wu, "Design of microstrip bandpass filters with multiorder spurious-mode suppression," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 12, pp. 3788–3793, Dec. 2005.

[15] C. H. Kim and K. Chang, "Wide-stopband bandpass filters using asymmetric stepped-impedance resonators," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 2, pp. 69–71, Feb. 2013.

[16] J.-T. Kuo and E. Shih, "Microstrip stepped impedance resonator bandpass filter with an extended optimal rejection bandwidth," *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 5, pp. 1554–1559, May 2003.

[17] K. U-yen, E. J. Wollack, T. A. Doiron, J. Papapolymerou, and J. Laskar, "A planar bandpass filter design with wide stopband using double split-end stepped-impedance resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 3, pp. 1237–1244, Mar. 2006.

[18] P. Chu, W. Hong, L. Dai, H. Tang, Z. Hao, J. Chen, and K. Wu, "Wide stop-band bandpass filter implemented with spur stepped impedance resonator and substrate integrated coaxial line technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 4, pp. 218–220, Apr. 2014.

[19] C. Quendo, E. Rius, C. Person, and M. Ney, "Integration of optimized low-pass filters in a bandpass filter for out-of-band improvement," *IEEE Trans. Microw. Theory Techn.*, vol. 49, no. 12, pp. 2376–2383, Dec. 2001.

[20] C.-W. Tang and M. G. Chen, "Wide stopband parallel-coupled stacked SIRs bandpass filters with open-stub lines," *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 12, pp. 666–668, Dec. 2006.

[21] R. N. Bates, "Design of microstrip spur-line band-stop filters," *Microwaves, Opt. Acoust., IEE J. on*, vol. 1, no. 6, pp. 209–214, Nov. 1977.

[22] W.-H. Tu and K. Chang, "Compact microstrip bandstop filter using open stub and spurline," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 4, pp. 268–270, Apr. 2005.

[23] H. Shaman and J. Hong, "Ultra-wideband (UWB) bandpass filter with embedded band notch structures," *IEEE Microw. Wireless Components Lett.*, vol. 17, no. 3, pp. 193–195, Mar. 2007.

[24] P. Chu, W. Hong, K. Wu, and L.-L. Dai, "Miniaturized wide stopband bandpass filter using in-resonator stub," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Seattle, WA, USA, Jun. 2013, pp. 1–3.

[25] X. Y. Zhang, J.-X. Chen, Q. Xue, and S.-M. Li, "Dual-band bandpass filters using stub-loaded resonators," *IEEE Microw Wireless Compon. Lett.*, vol. 17, no. 8, pp. 583–585, Aug. 2007.

[26] X. Y. Zhang and Q. Xue, "Novel centrally loaded resonators and their applications to bandpass filters," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 4, pp. 913–921, Apr. 2008.

[27] K. Wada and I. Awai, "Heuristic models of half-wavelength resonator bandpass filter with attenuation poles," *Electron. Lett.*, vol. 35, no. 5, pp. 401–402, Mar. 1999.

[28] F. Gatti, M. Bozzi, L. Perregrini, K. Wu, and R. G. Bosisio, "A novel substrate integrated coaxial line (SICL) for wide-band applications," in *Proc. 36th Eur. Microw. Conf.*, Manchester, U.K., Sep. 2006, pp. 1614–1617.

[29] F. Zhu, W. Hong, J.-X. Chen, and K. Wu, "Ultra-wideband single and dual baluns based on substrate integrated coaxial line technology," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 10, pp. 3062–3070, Oct. 2012.

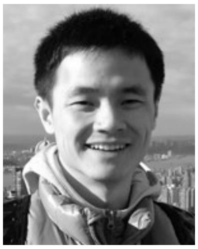
[30] P. Chu, W. Hong, K. Wu, J.-X. Chen, and H.-J. Tang, "A miniaturized bandpass filter implemented with substrate integrated coaxial line," *Microw. Opt. Technol. Lett.*, vol. 55, no. 1, pp. 131–133, Jan. 2013.

[31] Y. Shao, X.-C. Li, L.-S. Wu, and J.-F. Mao, "A wideband millimeter-wave substrate integrated coaxial line array for high-speed data transmission," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 8, pp. 2789–2800, Aug. 2017.

[32] J. Yin, Q. Wu, C. Yu, H. Wang, and W. Hong, "Broadband endfire magnetoelectric dipole antenna array using SICL feeding network for 5g millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 67, no. 7, pp. 4895–4900, Jul. 2019.

[33] F. Xu and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 66–73, Jan. 2005.

[34] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Application*, 1st ed. New York, NY, USA: Wiley, 2001.



PENG CHU (S'10–M'14) was born in Anqing, China, in 1985. He received the B.S. and M.S. degrees from Xidian University, Xi'an, China, in 2006 and 2009, respectively, and the Ph.D. degree from the State Key Laboratory of Millimeter Waves, Southeast University, Nanjing, China, in 2014. He joined the College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing, in 2014, where he is currently an Associate Professor. Since 2018, he has been a Postdoctoral Fellow with Poly-Grames Research Center, Polytechnique Montréal, Montreal, QC, Canada. His current research interests include the microwave and millimeter-wave circuits, antennas, and energy harvesting.

LEI GUO received the B.Eng. degree in communication engineering from the Harbin Institute of Technology, Harbin, China, in 2011, and the Ph.D. degree in electronic engineering from the City University of Hong Kong, Hong Kong, China, in 2016. From 2016 to 2019, she was a Postdoctoral Research Fellow with Poly-Grames Research Center, Polytechnique Montréal, Montreal, QC, Canada. She is currently an Associate Professor with the School of Information and Communication Engineering, Dalian University of Technology, Dalian, China. Her current research interests include dielectric resonator antenna, antenna in package, and energy harvesting. She was a recipient of the 2015 iWEM Student Best Paper Award. She served as the Organizing Committee Member and the Chair of the student best design and article competition of the 2018 IEEE MTT-S Wireless Power Transfer Conference, Montreal.

LONG ZHANG received the B.S. and M.S. degrees in electrical engineering from the Huazhong University of Science and Technology (HUST), Wuhan, China, in 2009 and 2012, respectively, and the Ph.D. degree in electronic engineering from the University of Kent, Canterbury, U.K., in 2017. He was a Postdoctoral Research Fellow with the Poly-Grames Research Center, Polytechnique Montréal, Canada, in 2018. He is currently an Assistant Professor with the College of Electronics and Information Engineering, Shenzhen University, Shenzhen, China. His current research interests include circularly polarized antennas and arrays, mm-wave antennas and arrays, phased arrays, tightly coupled arrays, and reflectarrays. He served as a Reviewer for several technique journals, including the IEEE Transactions on Antennas and Propagation, the IEEE Antennas and Wireless Propagation Letters, the *IET Microwaves, Antennas & Propagation*, and the *Electronics Letters*.

KE WU (M'87–SM'92–F'01) received the B.Sc. degree (Hons.) in radio engineering from the Nanjing Institute of Technology (now Southeast University), China, in 1982, the D.E.A. degree (Hons.) in optics, optoelectronics, and microwave engineering from the Institute National Polytechnique de Grenoble (INPG), in 1984, and the Ph.D. degree (Hons.) in optics, optoelectronics, and microwave engineering from the University of Grenoble, France, in 1987.

He was the founding Director of the Center for Radiofrequency Electronics Research of Quebec (Regroupement stratégique of FRQNT) and the Tier-I Canada Research Chair of RF and millimeter-wave engineering. He has held the guest, a visiting, and an honorary professorships with many universities around the world. He has been Director of Poly-Grames Research Center. He is currently a Professor of electrical engineering, and the endowed Industrial Research Chair with Future Wireless Technologies with the Polytechnique Montréal, University of Montreal, Montreal, QC, Canada. He is also with the School of Information Science and Engineering, Ningbo University, on leave from his home institution. He has authored or coauthored more than 1300 refereed articles and a number of books/book chapters. He has filed more than 50 patents. His current research interests involve substrate integrated circuits and systems, antenna arrays, field theory and joint field/circuit modeling, ultra-fast interconnects, wireless power transmission and harvesting, and MHz-through-THz technologies and transceivers for wireless sensors and systems, as well as biomedical applications, the modeling and design of microwave, and terahertz photonic circuits and systems.

Dr. Wu is a Fellow of the Canadian Academy of Engineering (CAE) and the Royal Society of Canada (The Canadian Academy of the Sciences and Humanities). He is a member of Electromagnetics Academy, Sigma Xi, URSI, and the IEEE-Eta Kappa Nu (the IEEE-HKN). He is also the inaugural representative of North America as a member of the European Microwave Association (EuMA) General Assembly. He was a recipient of many awards and prizes, including the first IEEE MTT-S Outstanding Young Engineer Award, the 2004 Fessenden Medal of the IEEE Canada, the 2009 Thomas W. Eadie Medal of the Royal Society of Canada, the Queen Elizabeth II Diamond Jubilee Medal, in 2013, the 2013 FCCP Education Foundation Award of Merit, the 2014 IEEE MTT-S Microwave Application Award, the 2014 Marie-Victorin Prize (Prix du Quebec - the highest distinction of Québec in the natural sciences and engineering), the 2015 Prix d'Excellence en Recherche et Innovation of Polytechnique Montréal, the 2015 IEEE Montreal Section Gold Medal of Achievement, and the 2019 IEEE MTT-S Microwave Prize. He has held key positions in and has served on various panels and international committees, including the Chair of Technical Program Committees, International Steering Committees, and international conferences/symposia. In particular, he was the General Chair of the 2012 IEEE Transactions on Microwave Theory and Techniques (IEEE MTT-S) International Microwave Symposium (IMS). He was the Chair of the joint IEEE Montreal chapters of MTT-S/AP-S/LEOS and then the restructured IEEE MTT-S Montreal Chapter, Canada. He has served the IEEE MTT-S and Administrative Committee (AdCom) as the Chair of the IEEE MTT-S Transnational Committee, a Member and Geographic Activities (MGA) Committee, a Technical Coordinating Committee (TCC), and the 2016 IEEE MTT-S President, among many other AdCom functions. He is currently the Chair of the IEEE MTT-S Inter-Society Committee. He was an IEEE MTT-S Distinguished Microwave Lecturer, from 2009 to 2011. He has served on the Editorial/Review Boards for many technical journals, transactions, proceedings, and letters, as well as scientific encyclopedia, including an Editor and the Guest Editor.